

# Model for Mercury Deposition from Smoke Plumes

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In: Intelligence in a Materials World, 2003, p. 615-628, CRC Press, Boca Raton, USA

## Abstract

A computer program has been developed to be used as a screening tool over the area of the Brazilian Amazon to assess the distribution of mercury deposited to the ground from smoke plumes originating from forest fires occurring over a year's time. The model is a steady state, point source, plume model that assumes a transverse Gaussian distribution for the plume. It is based on the traditional Gaussian plume technique, but has been augmented with additional features required for the present application. Among these, is the need to be run as an automatic process over more than 30,000 fires occurring in the Amazon annually. In addition, the model must accommodate ground deposition of material from the highly lofted plumes and the corresponding depletion of this material from the plumes. Rather than industrial stacks, the model is applied to ground-based fires covering large areas of ground and passing locally through various phases of fire development. None of these exist in the traditional Gaussian model. In order to accommodate these needs, sufficient data must be available at run time and is expected to come from several sources:

- Daily and/or archived weather data from an Amazon wide net of weather stations
- GIS layers containing the weather station locations
- GIS layers containing Amazon wide annual fire occurrence data
- GIS layers containing data on ground cover vegetation in the Amazon (keyed to look-up-tables with biomass and mercury data)

Dispersal and chemical speciation of mercury within the environment is complex and poorly understood. The present model attempts to deal with a part of this process: dispersal and deposition of metallic mercury via forest burning. It is a prototype model developed to run automatically as a screening tool, over the entire Brazilian Amazon to characterize mercury dispersal during the annual forest fire season. It is assumed that most of the anthropogenic mercury in the Amazon originates from gold mining-related activities. A method to estimate the amount of mercury coming from these sources has been developed, but is not described here.

## Introduction

Mercury is a unique atomic element. It is a heavy metal that is liquid at room temperature. It is also a poor conductor of heat, but a good conductor of electricity. Its boiling point, 357 °C, is near or below the melting point of most other metals. It is also known that some of the compounds of mercury, many of which occur in soil and water, are extremely toxic to humans and to animals, causing irreversible neurological damage and even death. Besides being a toxic agent, a liquid and a good conductor of electricity, mercury mixes readily with several other metals, such as tin, silver and gold, "dissolving" them to form amalgams. Silver amalgam, because it is relatively inert and easily worked, is used in dental fillings, but gold amalgam is used extensively in gold mining to extract gold from crushed ore and sediment. Once the gold is extracted, the mercury is removed by heating and is often allowed simply to boil off into the atmosphere without being recovered. Since mercury is an atomic element, once it is released into the environment, it does not go away but remains to be continually revaporized and redeposited over a large area, contaminating soil, water and living organisms [1, 2, 3, 4, 5].

The main problem with mercury, of course, is its toxicity. However, its other properties add to this problem, assisting in its dispersal and contamination of the environment. Because of its low vaporization temperature and high vapor pressure, mercury is volatile and easily vaporizes in fire. Since it readily adsorbs on carbon,

it adheres to smoke particles from forest fires which are lofted to high altitudes and carried long distances by the upper level winds. Mercury vapor emitted from gold mines and gold shops is of much lower temperature and is dominated by local winds and does not travel more than 2-3 km before settling to the ground. However, if it does settle upon surrounding vegetation, it can be revaporized by subsequent fires and then, lofted to great heights and carried large distances to be distributed over wide areas.

As mentioned, mercury amalgamation is used extensively to extract gold from its ores by artisanal mining operations. Since mercury recovery is seldom practiced, when the gold is separated from the mercury, the mercury vapor is often allowed to dissipate into the atmosphere to settle elsewhere. When the mined gold is then brought to the gold shops to be sold and melted into bars, as much as 5% of the mercury may still remain in the gold. When the gold is melted, this remaining mercury is vaporized into the atmosphere as well. Although the amount of remaining mercury may seem relatively small, the amount of gold processed by a shop over a year is relatively large. Moreover, gold shops are located in towns and cities in the midst of densely populated areas and the chance of dangerous contamination is very high.

Gold mines and gold shops are an important source of mercury contamination to the environment. However, the extensive dispersal of mercury within the environment depends greatly upon the occurrence of forest fires. Since natural fires are rare in the Amazon, the occurrence of forest burning is due mostly to its use as a deforestation agent for converting land use to agriculture and development. That is, most of these fires are anthropogenic. It is well recognized that, in industrial areas, the burning of coal is an important source of mercury contamination. However, in undeveloped areas, the burning of forests (a precursor to coal) has become an equal threat for mercury contamination. It would be useful to be able to characterize the mercury dispersion from such sources and to be aware of land areas and water supplies affected by this contamination. The present model is meant to furnish a tool for performing such a task.

### **Emission of Mercury from Forest Burning**

The amount of mercury emitted by a fire can be estimated from the amount of biomass affected by a burn and the amount of mercury contained in the biomass. Because of its low vaporization point, most of the mercury contained in the biomass is emitted early during the flash phase when the biomass is not yet entirely consumed by the fire. It is important, then, to know the location of the fire, the area burned, the vegetation ground cover affected and the biomass and mercury content of the ground cover. This information is available from a combination of GIS data layers, with data from both satellite and direct observation, and from parameter look-up-tables. The equations used to determine mercury emission are based on similar ones used to estimate emission of greenhouse gases and other pollutants from forest fires [19, 20, 21].

#### **Equation for Mercury from Burning:**

$$Hg(kg) = \sum_j^N f_{Hgj} \cdot (A_j \cdot B_j \cdot \alpha_j \cdot \beta_j) \quad 1.$$

where, for each vegetation category,  $j$ :

$Hg$  = Total amount of mercury released from the fire (kg)

$f_{Hgj}$  = Dry weight fraction of  $Hg$  within vegetation type  $j$ , i.e. kg per Tonne biomass  
(1 metric Tonne =  $10^6$  g = 2205 lbs).

$A_j$  = Area covered by vegetation type  $j$  (ha),

$B_j$  = Surface density of biomass within vegetation type  $j$  (e.g. Tonnes per hectare),

$\alpha_j$  = Percent of biomass that is above ground for vegetation type  $j$ ,

$\beta_j$  = Mercury release efficiency (percentage of available  $Hg$  released during the flash phase, generally 90% for all).

This equation can be summed over all vegetation subpolygons within each fire polygon. Calculation is performed on a subpolygon by subpolygon basis within the burned area. Once the amount of mercury emitted by a fire has been determined, its dispersion into the surroundings can be estimated using a set of weather parameters and the extended Gaussian Plume model.

## Standard Gaussian Model

The traditional Gaussian plume model is categorized as a static point source model that assumes all utilized parameters are constant during the lifetime of the plume, that material is emitted from a point source at a constant continuous rate and that no material is lost from the plume [6, 7, 8, 9, 10].

### Assumptions of the Model:

- Emission comes from a point source at a constant and continuous rate.
- Wind speed and direction are constant both in time and in elevation.
- Contents of the plume are lost neither by chemistry, nor by deposition. When the plume contacts the ground, the pollutant is reflected, not absorbed (no deposition).
- The surrounding terrain is limited to relatively flat, open country.
- Dispersion occurs only in the vertical and horizontal crosswind directions and is Gaussian distributed. There is no dispersion downwind.

### Standard Gaussian Plume Equation:

$$C(x, y, z) = \frac{Q_0}{ps_y s_z U_h} \exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{\Delta h - z}{s_z}\right)^2\right] \quad 2.$$

where:

$C(x, y, z)$  = Volume density of mercury in the smoke plume ( $\mu\text{g}/\text{m}^3$ )

$x$  = Downwind distance from source (m)

$y$  = Horizontal (crosswind) distance from plume centerline (m)

$z$  = Vertical (crosswind) distance from plume centerline (m)

$U_h$  = Windspeed at the effective stack height (m/s)

$\Delta h$  = Effective stack height (a sum of thermal lofting and the physical stack height) (m)

$Q_0$  = Mercury emission rate at the source, ( $\mu\text{g}/\text{s}$ )

$s_y, s_z$  = Dispersion coefficients, perpendicular to direction of propagation (m)

### Gaussian Dispersion Coefficients

The equations for the vertical and horizontal dispersion coefficients,  $s_y$  and  $s_z$ , depend only on the downwind direction,  $x$ . Input values of  $x$  are in kilometers, while  $s_y$  and  $s_z$  are output in meters. These equations, and others, have been developed to reasonably fit the nomographs often used to obtain these coefficients [11]. The parameters used in the equations below are empirical and depend upon the atmospheric stability class. Values of the parameters may be found in Table 3.

$$s_y = a \cdot x^{0.894}, \text{ the horizontal dispersion coefficient.} \quad 3.$$

$$s_z = c \cdot x^d + f, \text{ the vertical dispersion coefficient.} \quad 4.$$

### Extended Gaussian Plume Model

The traditional model has been extended here in order that deposition, depletion and thermal lofting of the plume can all be included. This model calculates a surface density distribution for the ground deposition of mercury, it can also furnish concentrations in the plume. The extended model has been prototyped in a Perl program which graphically displays contour plots of surface densities of ground deposit in selectable isopleths of mercury concentration. These additions are described in the following:

#### Additions to the model

- Windspeed is ordinarily measured at a nominal 10 meter height, however, the speed changes with height and terrain roughness. These adjustments are accommodated using available methods. The adjusted windspeeds must still remain constant throughout the analysis.

- Deposition of mercury from the plume is calculated for two processes: the gravitational settling of particles and contact between the plume and ground.
- Depletion of the plume from deposition is included as a continuous process.
- Forest fires have no stack (i.e. the physical height is zero). An "effective" stack height is calculated which includes the thermal lofting of the plume. Thermal lofting, of course, affects the subsequent deposition. An effective stack diameter is also estimated.

**Extended Gaussian Plume equation, with deposition and plume depletion:**

$$D(x, y) = \frac{Q(x) \cdot P(x)}{p \cdot s_y(x) \cdot s_z(x) \cdot U_h} \exp\left[-\frac{1}{2}\left(\frac{y}{s_y(x)}\right)^2\right] \int_{-\infty}^{\infty} \left(\exp\left[-\frac{1}{2}\left(\frac{\Delta h - z}{s_z(x)}\right)^2\right]\right) dz, \quad 5.$$

which furnishes the deposition density at the ground. The integral indicates that this equation has been integrated over the z direction to furnish the value 1.0. This is to simplify gravitational deposition. The parameters of the equation are:

- $D(x, y)$  = Surface density of mercury deposited to the ground ( $\mu\text{g}/\text{m}^2$ )
- $Q(x)$  = Depleted source term, which gives the diminishing rate (amount per second) of mercury available at a given downwind location,  $x$  ( $\mu\text{g}/\text{s}$ ).
- $P(x)$  = Deposition factor. Contains expressions for deposition due to both gravitational settling and plume/ground contact. This term is also a function of the downwind distance,  $x$  ( $\mu\text{g}/\text{m}^2$ ).
- $\sigma_y(x), \sigma_z(x)$  = Dispersion parameters in the y and z directions (i.e., perpendicular horizontally and vertically with respect to the downwind direction,  $x$ ). These coefficients are functions of  $x$  and increase monotonically with  $x$  (m).
- $\Delta h$  = The final thermal lofting height in the z direction. The final lofting altitude, once it is attained, is assumed to remain constant throughout the remainder of the plume. It represents the centerline of the symmetric Gaussian plume (km).

The remaining parameters are identical to those in Eq. 2.

The plume is assumed to disperse in a Gaussian manner only in the y and z directions, there is no dispersion in the x direction. It migrates in the x direction, downwind, at a constant speed. Within the plume, material is dispersed in a three dimensional density function. To facilitate the calculation of deposition, this density function is integrated over the z direction to obtain a two dimensional density function. The resulting plume concentration is given as the total columnar amount above and below some point at (x, y).

**Plume Lofting from Thermal Effects**

Since plumes from forest fires originate at ground level, the effective height (the sum of the physical and lofting heights) is due entirely to lofting from the heat of the fire. The height of thermal lofting can be calculated from the thermal buoyancy and momentum of the gases as they exit the fire; the temperature and stability of the surrounding atmosphere must also be considered. Because thermal lofting is important to the deposition process, a few words concerning this topic are appropriate [9, 10, 12, 13].

Hot gases, issuing from a fire, are lofted high into the atmosphere before the prevailing wind bends the plume over to carry it downstream. Thermal lofting adds substantially to the physical height of a stack to create an "effective" stack height (the sum of both these quantities). The effective stack height is often considerably greater than the physical stack height itself. In the case of a ground fire, the physical stack height is zero and the effective height is due entirely to thermal lofting. The amount of lofting depends on the inside diameter of the stack, the velocity and temperature of the hot gases exiting from the stack, as well as the atmospheric temperature and stability. In the case of forest fires, the physical stack has no height and the stack diameter is undefined. The temperature and velocity of the exiting gases are also difficult to know unless they are measured. Equations for the thermal lofting of ground fires are not available and, although

lofting is determined from the thermal buoyancy and vertical momentum of the gases, determining these values without actual measurement is difficult. As the gases rise, air and debris are entrained with them causing significant nonuniform cooling and the addition of a substantial amount of mass. This can produce large errors in the estimation of exit temperatures and velocities. Due to these uncertainties and the lack of a well defined effective stack radius, a more heuristic approach has been adopted. Use of a set of assumptions and approximations has allowed the employment of existing equations and the ability to automate their use over the Amazonian fires. These assumptions are itemized in the following:

- In general, a forest fire can be divided into two phases: the flash phase, which is the initial, short lived and very hot, phase (a few hours in length); and the smoldering phase, which follows at a much lower temperature and may last as long as several days. For any large burning area, only a portion is in flash phase at any particular time, some is smoldering and some has not yet been burned. Since almost all of the mercury (as much as 90%) contained in the burned vegetation will be vaporized during the flash phase, this is the only phase that will be considered here.
- In order to determine a mercury emission rate for the plume calculation and to estimate the amount of downwind migration of the plume during the fire, it is important to know the total lifetime of the fire (flash phase). Since the lifetime is not known for each fire evaluated, it must be estimated by the program. As a first approximation, it is assumed that the fire lifetime is linearly proportional to the area of the fire scar (many of these fires are about 1 ha in size, but some are as large as 100 ha [18]). In reality, this lifetime will depend to some extent on the material consumed and the conditions of the fire. If  $A$  is the area of the burn scar in hectares, the lifetime is estimated by the following:

$$T(s) \approx 1800 \cdot A \quad 6.$$

where  $A$  is in ha and  $T$  is in seconds (i.e., a half hour flash phase per ha).

- The average value of the emission rate at the source is estimated to be the total amount of mercury released (calculated above) divided by the lifetime of the fire:

$$Q_0(\text{mg}/s) \approx \frac{(10^9) \cdot Hg(\text{kg})}{T(s)}, \text{ given as } \mu\text{g/s}. \quad 7.$$

Of course, the emission rate downstream will be less, due to continued depletion of the plume.

- The calculation of plume rise from a smoke stack depends on the inside radius of the stack. Since forest fires have no stack, it is assumed that an equivalent radius can be associated with the flash phase of a fire. Estimation of an equivalent stack radius for a ground fire is complicated by the fact that only a small portion of the burned area is actually in the flash phase at any particular time. The equivalent stack radius should be a function of this area and the actual lofting height will vary greatly with the size of the flash area. Although location of the flash phase portion will vary over time, the amount of area involved,  $A_0$ , is assumed to be relatively constant and equal to approximately 0.05 to 0.1 hectares. This area is independent of the total area burned during the fire (the fire scar), but may depend somewhat on the material consumed and the environmental and climatological conditions of the fire itself.
- If this flash phase area is approximately circular (probably true, even when the fire scar is noncircular), a radius,  $r_0$ , can be estimated from the equation:

$$r_0 = \sqrt{\frac{A_0}{\pi}}. \quad 8.$$

If  $A_0$  is 0.05 – 0.1 ha, then  $r_0$ , the equivalent stack radius, is 12.6 - 17.8 m, respectively. This furnishes an estimate of the radius used for calculating thermal lofting.

- According to airborne MODIS measurements made during the SCAR-B experiments [18], the flash phase temperature of a forest fire is approximately  $1000 \pm 200$  K, the smoldering phase is  $600 \pm 100$  K. Since the exit gases are cooler than the fire itself and are further cooled by entrainment of surrounding gases, consider that the exit gas temperature,  $T_s$ , from a flash phase fire is of the order of 500 - 600 K.
- The exit velocity,  $V_s$ , of the gases from a fire will vary with the area of the flash phase and with the mass of the entrained gases and debris. It is assumed that the gas exit velocity in the present model is on the order of 10 m/s, or about 22.5 mph (36 km/h).

With these assumptions and estimated values, the lofting heights and related parameters can be calculated, using the conventional equations listed below.

**Final Lofting Height in a Stable Atmosphere: state = E, F:**

$$\Delta h = 2.6 \cdot \left( \frac{F}{U \cdot S} \right)^{\frac{1}{3}}, \quad 9.$$

**Final Lofting Height in an Unstable Atmosphere: state = A & ZD:**

$$\Delta h = \frac{1.6 \cdot F^{\frac{1}{3}} \cdot X_f^{\frac{2}{3}}}{U}. \quad 10.$$

Note that these equations for  $\Delta h$  differ between stable and unstable atmospheres. The parameters,  $F$ ,  $S$  and  $X_f$ , used above, are defined in the following equations:

**Buoyancy Flux Parameter:**

$$F = g \cdot r_0^2 \cdot V_s \cdot \left( 1 - \frac{T_a}{T_s} \right). \quad 11.$$

**Stability Parameter:**

$$S = \frac{g}{T_a} \left( \frac{\Delta T_a}{\Delta Z} - \Gamma_d \right) \approx \frac{g}{T_a} \left( \frac{\Delta T_a}{\Delta Z} + 0.01 \right) \quad 12.$$

Where  $\Gamma_d = -9.76 \cdot 10^{-3} \text{ } ^\circ\text{K/m} \approx -0.01$  is the dry adiabatic lapse rate, it gives the ideal adiabatic expansion and cooling of rising moisture free air. If the air is moisture laden, this value is smaller. The quantity,

$\frac{\partial \Theta}{\partial Z} = \left( \frac{\Delta T_a}{\Delta Z} - \Gamma_d \right)$ , is called the ‘‘potential’’ temperature gradient. It is the difference between the dry

adiabatic lapse rate and the ambient air temperature gradient. The potential temperature gradient is used to characterize the atmospheric stability. In these expressions,  $\Delta Z(m)$  is the total altitude change, and  $\Delta T_a(^{\circ}\text{K})$  is the change in ambient temperature over  $\Delta Z$ . The three different vertical temperature gradients should not be confused.

**Downwind Distance to the Point of Final Plume Rise:**

$$x_f = 120 \cdot F^{\frac{2}{5}}, \quad F \geq 55, \quad 13.$$

$$x_f = 50 \cdot F^{\frac{5}{8}}, \quad F < 55. \quad 14.$$

This is the point where the plume is considered to have stopped rising and continues downwind at a constant height. The above value of  $F$  determines if the plume is buoyancy or momentum dominated.

**Downwind Distance to the Plume/Ground Contact point:**

$$x_c = \left( \frac{((\Delta h)/2.15) - f}{c} \right)^{\frac{1}{d}}, \tag{15}$$

where  $c$ ,  $d$  and  $f$  are parameters used to calculate  $s_z$  (see Table 3).

This is the ground contact reference point, where plume concentration at the ground is 10% of maximum.

**Atmospheric Stability State**

The height of thermal lofting, the plume dispersion factors and the wind speed vertical profile all depend critically on the stability of the surrounding atmosphere. The stability, in turn, depends on the ambient vertical temperature gradient and the degree to which it deviates from the dry adiabatic lapse rate,  $G_d$ . Atmospheric stability is categorized into six states, A - F, ranging from Extremely Unstable to Moderately Stable [6]. The stability is influenced by windspeed, solar radiation and the resultant heating of the ground. Stability classes can be estimated from the well known Pasquill look-up table in Table 2 [14]. Parameters for the dispersion coefficients ( $a$ ,  $c$ ,  $d$  and  $f$ ) are obtained on the basis of atmospheric stability as in Table 3.

**Table 1.** Definitions of Atmospheric Stability States.

Class	Designation	Example conditions
A	Extremely Unstable	Low wind speed, clear bright day
B	Moderately Unstable	Low wind speed, some cloud cover
C	Slightly Unstable	Moderate wind speed, some cloud cover
D	Neutral	Moderate to strong wind, cloud cover or night
E	Slightly Stable	Low wind speed, cloudy night
F	Moderately Stable	Low wind speed, clear night

**Table 2.** Pasquill Atmospheric Stability Classification.

Surface wind Speed @ 10 m elevation (m/s)	Day solar insolation			Night Cloudiness	
	Strong	Moderate	Slight	Cloudy (≥ 4/8)	Clear (< 4/8)
< 2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

**Estimating Degree of Insolation:**

- Strong: Clear summer day: sun elev > 60 deg; solar radiation > 143 cal/m<sup>2</sup>/sec.
- Moderate: Summer day: few broken clouds or clear, sun elev 35 6 60 deg; solar radiation: 72 6 143 cal/m<sup>2</sup>/sec.
- Slight: Fall afternoon, cloudy summer day, or clear summer day: sun elev 15 6 35 deg; solar radiation < 72 cal/m<sup>2</sup>/sec.

If class is hyphenated, use average of values resulting from each.  
For overcast conditions, day or night, any wind speed, assume class D.

Once the stability state is known, parameters for  $\sigma_y$ ,  $\sigma_z$ , in the previously defined equations 3 and 4, can be obtained from Table 3 [6, 7, 10]:

**Table 3: Coefficients for  $s_y$ ,  $s_z$  and Windspeed Adjustment Parameters**

Stability	$a$	$x \# 1 \text{ km}$			$x > 1 \text{ km}$			Windspeed at $Z_h$	
		$c$	$d$	$f$	$c$	$d$	$f$	$p_r$	$p_u$
A	213	440.8	1.941	9.27	459.7	2.094	-9.6	.07	.15
B	156	106.6	1.149	3.3	108.2	1.098	2.0	.07	.15
C	104	61.0	0.911	0.0	61.0	0.911	0.0	.10	.20
D	68	33.2	0.725	-1.7	44.5	0.516	-13.0	.15	.25
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34.0	.35	.30
F	34	14.35	0.740	-0.35	62.6	0.180	-48.6	.55	.30

The last two columns of Table 3 contain coefficients used to calculation of the vertical wind profile. The wind profile equation gives the wind velocity at altitude  $Z_h$ , given a velocity measured at altitude  $Z_m$ :

$$U_h = U \cdot (Z_h/Z_m)^n . \quad 16.$$

Where, the exponent  $n$  is  $p_r$  for rural areas and  $p_u$  for urban areas.  $U_h$  is the velocity at the desired altitude and  $U$  is the measured velocity. Meteorological measurements of wind velocity are usually made at a height of 10 meters in a fairly open area. It is assumed, then, that  $Z_m$  is 10 and application is in a rural area, such as the Amazon:

$$U_h = U \cdot (Z_h/10)^{p_r} . \quad 17.$$

#### Automation of the Stability State Calculation

At a site, the atmospheric stability depends upon the windspeed, the amount of solar irradiation (insolation) at the ground level and upon the resulting vertical ambient temperature gradient. Solar insolation, in turn, depends upon the sun elevation angle and the amount of local cloud cover. In addition to windspeed then, estimation of atmospheric stability must be based upon sun angle and cloud cover.

Most fires occur at substantial distances from the daily reporting weather stations. Using inverse distance weighting, weather data is interpolated to the fire site from all stations within 100 km from the fire. However, because cloud cover data and precipitation occurrence do not interpolate well, such data is useful only if a fire site is within 50 km of a reporting weather station. If a fire site is beyond this distance, or if the data is non-existent, it is assumed that cloud cover is less than or equal to 2/8's and that rain has not occurred (a very common condition during the Amazon burning season). If rain does occur, no calculation of a plume is performed since the rain will ground all particulate matter in the atmosphere.

Calculation of the sun angle at a fire site requires the use of a known set of equations using the date and time of the fire occurrence and the latitude and longitude of the site. Equations for the sun angle calculation were obtained from Jean Meeus [15] and from John Caldwell [16]. Time estimation need not be exact for this calculation since only an approximate sun angle ( $\forall 3^\circ$ ) is needed.

The average solar irradiation at the top of the atmosphere is approximately 326 cal/m<sup>2</sup>/sec. However, even on a clear day, this value is much reduced at ground level due to atmospheric filtering. In addition, the amount of irradiation available at a fire site is still a fraction of this filtered amount due to the varying sun angle and from masking by cloud cover. Irradiation by the sun varies directly with the sine of the sun angle and negatively with the fraction of cloud cover masking. The final irradiation fraction (i.e., the fraction of the available amount) is assumed to be proportional to a product of these two factors. Once the irradiation fraction and the windspeed are known, it is possible to estimate the stability using Table 2.

## Deposition

Deposition from the plume is a function of at least two processes, the gravitational settling of particles, and the absorption or adherence of particles upon contact with the ground.

### Particle Settling Velocity

Beginning with the first of these, deposition from gravitational settling is related to the particle settling velocity. If the particle size is greater than a micron (smaller particles are influenced by Brownian motion), the settling velocity can be computed using a simplified form of Stoke's equation [6]. This equation was originally formulated to determine the terminal velocity of a falling spherical particle, taking into account gravitational acceleration and aerodynamic drag. It is also effective for our use, however, the particle diameter used in the equation is assumed to be that of an aerodynamically equivalent sphere.

$$v = (d^2 \cdot \rho \cdot g) / (18 \cdot \eta) \quad 18.$$

where,

$g$  = gravitational acceleration = 9.8 m/s<sup>2</sup>

$d$  = particle diameter (m)

$\rho$  = mass density of the particle (g/m<sup>3</sup>)

$\eta$  = viscosity of air = 0.0172 (g/m-s)

$v$  = particle settling velocity (m/s)

For the model, it is assumed that the settling velocity is constant throughout the plume and that its value is obtained using the average diameter of the particles in the plume. The resulting particle removal rate will also be constant. The actual particle settling fraction is given as the ratio of the settling velocity to the wind velocity, multiplied by the concentration at the point being considered. If the Settling Fraction is:

$$p_{grav} = v / U_h, \quad 19.$$

then the concentration deposited at  $(x, y)$  from gravitational settling is given as:

$$D_0(x, y) = p_{grav} \cdot C(x, y) \mu\text{g}/\text{m}^2, \quad 20.$$

$C(x, y)$  is the mercury concentration in the depleted plume and differs from that in Eq. 2.

### Deposition from Ground/Plume Contact

In this model, the plume is described as a Gaussian distribution in the  $y$  and  $z$  directions. This implies, mathematically at least, that the distribution extends from negative to positive infinity and, to some degree, the plume is always in contact with the ground. In practice, the tails of the plume distribution are not well-defined and it is useful to use some reference point where contact can be assured. This reference point will be defined as that location where  $Dh$  is 2.15 times  $s_z(x)$ , the vertical dispersion factor. At this point, the concentration is 10% of the value at  $Dh$ , the maximum of the Gaussian.

The second process for deposition is due to the adherence of particles when contact occurs between the plume and the ground. While gravitational settling takes place continuously and at a small rate throughout the length of the plume, the total deposition rate increases considerably beyond the point where contact occurs. Beyond this point, a substantial amount of additional pollutant is transferred from the plume to the ground through particle adherence. The amount actually deposited is proportional to several factors: the Hg

concentration in the plume, the fraction of the plume subtended by the ground and an efficiency factor (i.e., the fraction of contacted material that actually adheres to the ground).

The shape of the plume is a quasi-ellipsoidal cone that is Gaussian distributed perpendicular to the axis. The major and minor axes of the cross-section are proportional to the cross-wind dispersion factors,  $\mathbf{s}_y$  and  $\mathbf{s}_z$ . In the present development, it is assumed that once the maximum plume height is attained at  $X_f$ , the plume center remains at a constant height (i.e.,  $\mathbf{D}h$ ) above the ground. But because the dispersion factors are increasing with  $x$ , the plume expands continuously as it travels downwind and eventually contacts the ground. After this point, it can be considered that a portion of the Gaussian plume is subtended by the ground and that a fraction of the pollutant adheres and is deposited. The amount deposited onto the ground is proportional to the subtended fraction and can be calculated as the area under the tail of the Gaussian.

To perform this calculation at some distance,  $x$ , downwind from the source, normalize the variable of the integral to  $\mathbf{s}_z(x)$ , and evaluate the subtended portion of the Gaussian as  $Int_c(x)$ . This value gives the portion of the plume subtended by the ground. Only a fraction of the subtended plume actually adheres and is deposited. The remainder is reflected back into the airborne plume. Gravitational settling continues to occur in the airborne portion and contributes in addition to that deposited from ground contact.

The origin of the  $z$  coordinate is at ground level and normalization gives:  $z' = z/\mathbf{s}_z(x)$ . The integral of the subtended part of the plume is given by:

$$Int_c = P_{cont} = \int_{\left(\frac{\Delta h}{\mathbf{s}_z(x)}\right)}^{\infty} e^{-\frac{1}{2}(z')^2} dz' \quad 21.$$

Referring back to equation 7, the Gaussian expression for ground deposition is:

$$D(x, y) = \frac{Q(x) \cdot P(x)}{\mathbf{p} \cdot \mathbf{s}_y(x) \cdot \mathbf{s}_z(x) \cdot U_h} \exp\left[-\frac{1}{2}\left(\frac{y}{\mathbf{s}_y(x)}\right)^2\right] \int_{-\infty}^{\infty} \exp\left[-\frac{1}{2}\left(\frac{\Delta h - z}{\mathbf{s}_z(x)}\right)^2\right] dz, \quad 22.$$

the integral term evaluates to 1.0. The term,  $P(x)$ , the total deposition factor, is:

$$P(x) = (P_{grav}(x) + f_{cont} \cdot P_{cont}(x)). \quad \text{This is the fraction deposited to the ground at } x. \quad 23.$$

$P_{cont} = Int_c$ , is the total amount available from contact;  $f_{cont}$  (the sticking efficiency factor) is the fraction actually deposited from contact;  $P_{grav}$  is the amount deposited from gravitational settling.

The term,  $f_{cont}$ , is constant and can be estimated using concepts from filtering technology [17]. It is necessary to take into account, among other factors, the size of the particles, the type of ground vegetation and the roughness of the terrain. However, since this process is used for wholesale application, these parameters may not be available for all sites on a general basis. As a result, this term can be edited and is arbitrarily set to a value between 0.05 and 0.1.

$P_{grav}$  is the amount of deposition from gravitational settling, as described previously.

$Q(x)$  ( $\mu\text{g/s}$ ) is the depleted source term, the downstream emission rate at  $x$ . It is the total amount of mercury per second available downwind after all deposition previous to  $x$  has been subtracted. The equation for  $Q(x)$  is self iterative and refers back to previous values of  $Q(x)$  at each  $\Delta x$  step. The depletion process developed here is an attempt to address some issues presented by Gifford in [13]. The equation for  $Q(x)$ , in  $\mu\text{g/s}$ , is:

$$Q(x) = Q(x - \Delta x) \cdot \left( 1 - P(x - \Delta x) \cdot \left( \frac{\Delta x}{\Delta x_0} \right) \right), \text{ the fraction remaining in the plume at } x. \quad 24.$$

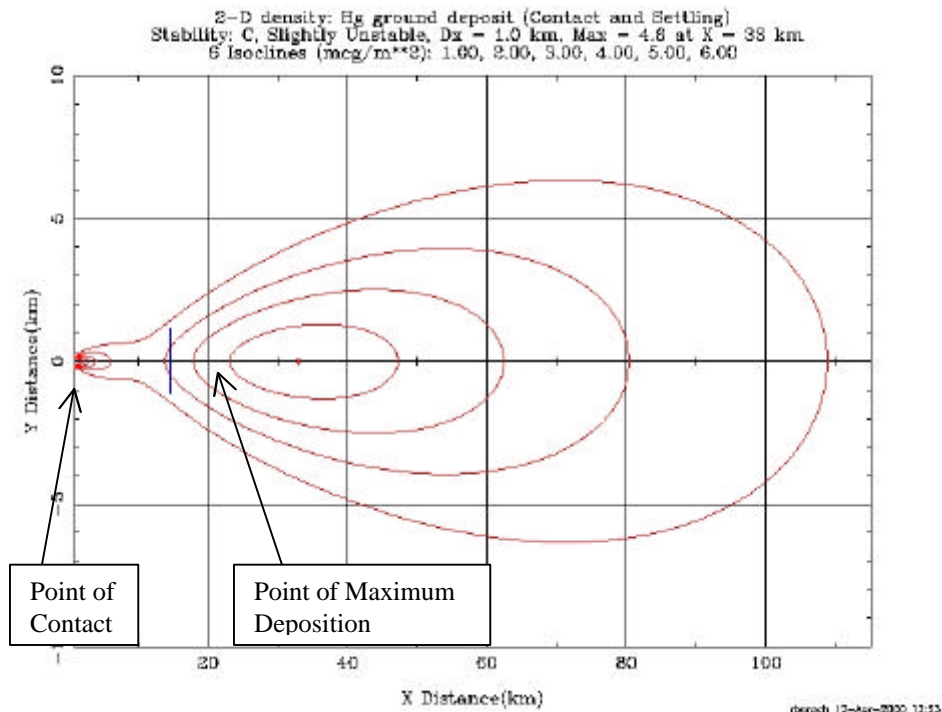
At the origin, the initial source term is:  $Q(0) = Q_0$ . The term,  $\Delta x$ , is the increment of the depletion integral. The term,  $\Delta x_0$ , is the default increment size (usually unity). Inclusion of  $(\Delta x / \Delta x_0)$  compensates for assigning various sizes to  $\Delta x$  to obtain different levels of precision for different problems.

Depletion affects the internal density distribution of the plume, lowering the height of the center line and skewing the gaussian distribution. Several approaches exist for modeling these effects, however, such characterizations are not included in this approximate model since they are at a higher order and are useful only for a more detailed analysis. It is assumed that, once the maximum lofting height is attained, the plume remains at a constant height and that the Gaussian distribution within the plume is unskewed.

A large number of fires and their resulting plumes occur during a year's time. Deposits from many of these plumes overlap, creating multiple deposits over the same areas of ground. It is important, then, to account for these cumulative deposits by summing the concentration levels, not only from those within an area of interest (AOI), but also those from surrounding areas with plumes impinging into the AOI. All plumes are calculated within the AOI as well as in the surrounding areas before the final summation.

### Example Output

The following plot is an example output from the Perl prototype program. Ground deposits are shown from both gravitational settling and plume/ground contact. This is a stand-alone plot that has not been transferred to a basemap. In this example, the  $1 \mu\text{g}/\text{m}^2$  isocline is about 108 km by 13 km in size. The other displayed isopleths are at 2, 3, and  $4 \mu\text{g}/\text{m}^2$ . The maximum deposit is at  $4.66 \mu\text{g}/\text{m}^2$ . This plot is further explained by the table in Fig. 2. The plume shape differs from the traditional teardrop since deposition from ground contact is not at a constant rate, but varies with downwind position.



**Fig. 1.** Annotated Output Plot from the Prototype Program.

04/12/2000

## LOFTING PARAMETERS

11:43:30

U = 6 m/s, inpA = 0.05 ha, Ts = 600 K, Ta = 300 K, State: C  
 dTHdz = -1.6e-02, p<sub>0</sub> = 7.9e-04, fracc = 0.05, diam = 10.0 μm

inpA ha	Rise		POC		r <sub>0</sub>
	delh km	X <sub>f</sub> km	X <sub>C</sub> km		
0.05	1.40	4.3	13.5	12.6	

Settling velocity: 4.75e-03 m/s  
 Settling fraction (p<sub>0</sub>): 7.92e-04  
 Contact point (X<sub>C</sub>): 13.5 km  
 Max Deposit at X = 33.0 km: 4.66 μg/m<sup>2</sup>

## Hg Concentration (at y = 0)

Travel Dist X km	Plume S & C mg/m <sup>2</sup>	Deposit S & C mg/m <sup>2</sup>
0.0	1.0	0.00
5.0	3021.0	2.39
10.0	1619.2	1.47
15.0	1119.7	2.31
20.0	853.5	3.51
25.0	681.9	4.29
30.0	559.1	4.62
35.0	465.7	4.63
40.0	391.9	4.46
45.0	332.3	4.19
50.0	283.2	3.86
55.0	242.4	3.52
60.0	208.1	3.18
65.0	179.1	2.86
70.0	154.5	2.56
75.0	133.4	2.28
80.0	115.4	2.03
85.0	100.0	1.80
90.0	86.7	1.59
95.0	75.3	1.41
100.0	65.4	1.24

## Definitions

U - Wind Speed  
 inpA - Actual area of flash phase  
 Ts - Gas escape temperature  
 Ta - Ambient temperature  
 State - Stability state  
 dTHdz - Ambient vert. temp. gradient  
 p<sub>0</sub> - Gravitational settling rate  
 f racc - Actual contact dep. fraction  
 diam - Average particle diameter  
 delh - Height of thermal lofting  
 X<sub>f</sub> - Distance to final rise point  
 POC X<sub>C</sub> - Point of ground contact  
 r<sub>0</sub> - Equivalent stack radius  
 S & C - Settling and Contact deposition

**Fig. 2.** Tabulation of Input Data and Ground Concentration

The above figure contains a tabulation of the input data and resulting ground concentrations at Y = 0 for the plume plotted in Fig. 1. The inset box contains the definitions for all quantities referenced in the data tables.

## References

1. Marcello M. Veiga, John A. Meech, 1995, A Brief History of Amalgamation Practices in the Americas. 16th Brazilian Symp. on Ore Process. and Hydrometallurgy, Rio de Janeiro, Sept. 3 - 6, 581-594.
2. M.M. Veiga, J.A. Meech, N. Onate, 1994, Mercury Pollution from Deforestation, *Nature*, 368, 816
3. M.M. Veiga, J.A. Meech, D. Tromans, 1995, Mercury Emissions and Stability in the Amazon Region, Proc. Inter. Sym. On Waste Disposal, 34<sup>th</sup> Ann. Conf. of Metal CIM, Vancouver
4. E.T. Fernandes, R.C. M. Alves, S. Hacon, P. Artaxo, R.C. Campos, 1997, Dispersão de Mercúrio Atmosférico em Alta Floresta, (internal report from PADCT project)
5. L.D. Lacerda, M.G. Ribeiro, R.C. Cordeiro, A. Sifeddine, B. Turcq, 1999, Atmospheric Mercury Deposition Over Brazil During the Past 30,000 Years, *Ciencia e Cultura Journal of the Brazilian Association for the Advancement of Science*, p. 363, Vol. 51 (5/6), Sept./Dec.
6. G.M. Masters, 1991, Introduction to Environmental Engineering and Science, 2<sup>nd</sup> Ed., Prentice Hall
7. G. Kiely, 1996, Environmental Engineering, McGraw-Hill
8. A.K. Blackadar, 1997, Turbulence and Diffusion in the Atmosphere, Springer
9. User's Guide for the Industrial Source Complex Dispersion Models, Volume II - Description of Model Algorithms, USEPA, Sept., 1995, EPA-454/B-95-003b
10. M.R. Beychok, 1994, Fundamentals of Stack Gas Dispersion, 3<sup>rd</sup> Ed.
11. D. O. Martin, 1976.
12. G.A. Briggs, 1975, Plume Rise Predictions; chap. 3, Lectures on Air Pollution and Environmental Impact Analyses, AMS, 9/29 - 10/3
13. F. A. Gifford, 1975, Atmospheric Dispersion Models for Environmental Pollution Applications; chap. 2, Lectures on Air Pollution and Environmental Impact Analyses, AMS, 9/29 - 10/3
14. F. Pasquill, 1974, Atmospheric Diffusion, 2<sup>nd</sup> Ed., John Wiley and Sons
15. J. Meeus, 1998, Astronomical Algorithms, 2<sup>nd</sup> Ed., Willmann-Bell
16. J. Caldwell, 1999, "Approximate Position of the Sun From Any Location At Any Time", at: [www.saao.ac.za/sky/sunposn.html](http://www.saao.ac.za/sky/sunposn.html)
17. W.C. Hinds, 1982, Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, Wiley & Sons.
18. Y.J. Kaufman, R.G. Kleidman, M.D. King, 1998, SCAR-B fires in the tropics: Properties and remote sensing from EOS-MODIS, *J. of Geophysical Research*, 103, p.31,955
19. J.S. Levine, 1994, Biomass Burning and the Production of Greenhouse Gases, chap. 9 in Climate Biosphere Interaction: Biogenic Emissions and Environmental Effects of Climate Change, R.G. Zepp, Ed.
20. D.L. Skole, B.M. Moore III, W.H. Chomentowski, 1994, Spatial Analysis of Land Cover Change and Carbon Flux Associated with Biomass Burning in Brazil, 1970 - 1980, chap. 10 in Climate Biosphere Interaction: Biogenic Emissions and Environmental Effects of Climate Change, R.G. Zepp, Ed.
21. W. Seiler, P.J. Crutzen, 1980, Estimates of Gross and Net Fluxes of Carbon Between the Biosphere and the Atmosphere from Biomass Burning, *Climate Change*, 2, 207